Acoustic Considerations Involved in Steady State Loud Speaker Measurements

By L. G. BOSTWICK

SYNOPSIS: Certain difficulties encountered in acoustic measurements of the performance of loud speakers are described. Because of the nature of these difficulties it has not yet been possible to specify a complete and simple set of measurements or conditions which will completely express the performance of a loud speaker. Data are given showing the performance of two representative types of loud speakers both when measured in outdoor space free from reflections and when measured under varying conditions in a specially treated acoustic laboratory. The differences serve to emphasize the importance of certain precautions in the making of indoor acoustic measurements.

SCOPE

IN view of the general misconception of the meaning of many claims which are made regarding the operation of loud speakers, it appears desirable to discuss in some detail the requirements which should be taken into account in making measurements for setting up ratings of loud speaker performance. For example, claims to "uniform response at all frequencies in the audible range" or "flat characteristic" can not be accurately applied to loud speakers which have thus far been made available. In many cases the claims for a loud speaker are based upon carefully made electrical measurements but these are often obtained in such a manner and under such conditions that they do not represent the performance of the loud speaker as it would be normally observed, and therefore are misleading. The main consideration in making loud speaker measurements is not the electrical circuit arrangement or apparatus of the measuring system but rather the acoustic conditions under which the magnitude of the sound output of the loud speaker is determined. It is the purpose of this paper to discuss steady state loud speaker measurements particularly from the standpoint of the more important acoustic factors which are involved and which must be properly considered in order to be able to interpret the significance of any measurements obtained.

LOUD SPEAKER PERFORMANCE INDICES AND FACTORS INVOLVED IN THEIR DETERMINATION

Efficiency.—In power engineering and other branches of engineering, efficiency (a measure of the degree to which a device performs the functions for which it is designed) is defined as the ratio of the power delivered to a load to the power absorbed from a source of

supply. Since in power transmission systems the purpose of a machine is to draw a limited amount of power from a relatively unlimited source and to deliver this power to a load with a minimum loss in the machine itself, this ratio constitutes a useful measure of the performance. If it were of interest a similar quantity could likewise be used as a measure of the performance of a loud speaker. In this latter case however, the function is not in general to draw a limited amount but as much power as possible from a supply source and to radiate maximum power to the air or load. A measure of the efficiency would therefore have to involve the ability of the loud speaker to take maximum power from the supply and might be defined as the ratio of acoustic power P_A radiated to the maximum electrical power P_E which the supply circuit is capable of delivering under optimum impedance conditions. Thus the efficiency η at a specified frequency would be defined by the ratio

$$\eta = \frac{P_A}{P_E}. \tag{1}$$

Assuming the impedance of the electrical supply source for a loud speaker essentially non-reactive (as is almost invariably the case) and of a constant magnitude r suitable to the requirements of the loud speaker, then the maximum power which the supply circuit is capable of delivering under optimum impedance conditions with an open circuit supply voltage e would be

$$P_E = \frac{e^2}{4r}. \tag{2}$$

These quantities are all readily measureable. The determination of the quantity P_A however is more difficult.

For measuring the acoustic energy or power stored in or transmitted through the medium adjacent to a loud speaker, the condenser transmitter is probably the most suitable free space acoustic measuring device. The ruggedness of this transmitter for an instrument of this type and the straightforward manner in which it can be used recommend it for practical loud speaker measurements. The condenser transmitter is not, however, an acoustic power indicating device but is a device having a high impedance compared to the impedance of the acoustic system in which it is used. It is therefore an acoustic measuring device which is analogous to an electrical voltmeter and can be calibrated by the thermophone [1] or other means to measure the excess pressure in a medium resulting from a sound wave. Other acoustic measuring devices such as the Rayleigh disc, thermal devices

[1] "The Thermophone," E. C. Wente, *Physical Review*, Vol. XIX, No. 4, April, 1922.

of different kinds, etc. can of course be used but these in general are considerably more difficult to use than the condenser transmitter, especially for free space acoustic measurements and the measured quantities bear no more simple relation to the acoustic power or energy.

Assuming the condenser transmitter then to be the acoustic measuring or indicating device, the problem becomes one of how and where in the medium to measure the pressure so that the measurement will bear some readily deducible relation to the acoustic power delivered by the loud speaker. The answer depends upon the nature of the acoustic medium in which the measurements are made. The simplest relations between excess r.m.s. pressure in the medium and the acoustic power exist when the pressure measurements are made in an infinite medium or in a room in which the incident energy at the walls is completely absorbed. Under such conditions the acoustic power from a loud speaker could be obtained by measuring the pressure at all points on the surface of a sphere having a radius several times that of the largest dimension of the sound radiating surface and with the sound radiating surface at the center of the sphere. The acoustic power would then be

$$P_A = \frac{1}{\rho c} \int\int p^2 ds, \tag{3}$$

[2]

where ρ is the density of the air; c is the velocity of sound propagation; p is the excess r.m.s. pressure; and ds is the surface of the sphere. This relation, however, is generally true only when the radius of the spherical surface is sufficiently large so that the sound radiating surface appears as a point source. From equations (1), (2) and (3) the efficiency of a loud speaker could then be expressed in terms of excess pressure measurements over the surface of the sphere in an infinite medium as follows:

$$\begin{aligned} \eta = \frac{P_A}{P_E} &= \frac{1}{\rho c} \frac{\int\int p^2 ds}{\frac{e^2}{4r}} \\ &= \frac{K \int\int p^2 ds}{\frac{e^2}{r}} . \end{aligned} \tag{4}$$

Within an enclosure where there are sound reflections from the bounding surfaces, the determination of the acoustic power delivered by a loud speaker would involve the measurement of the pressure at

[2] "Theory of Vibrating Systems and Sound," Crandall, pp. 92 and 120.

all points within the enclosure in order to obtain the average energy density and then making use of known relations between energy density and the rate of energy flow into the room. Under steady state conditions, the total potential energy stored within the room would be

$$E_p = \frac{1}{2\rho c^2}\int\int\int p^2 dv.^3 \tag{5}$$

Assuming the room to be large so that the region within say a wave-length of the loud speaker is a small portion of the total volume of the room, it can be said with a reasonable approximation that the potential and kinetic energies stored within the room as the sound is transmitted are equal. The total energy would therefore be twice the potential energy or

$$E = 2E_p = \frac{1}{\rho c^2}\int\int\int p^2 dv. \tag{6}$$

This latter statement may be roughly justified in a simple manner by considering the sound radiated by the loud speaker as consisting of two components, one of which is completely absorbed at the walls and the other completely reflected. In considering separately that component which is absorbed, the loud speaker can be thought of as in an infinite medium and under these conditions (excluding the region within say a wave-length of the loud speaker) the acoustic impedance of the medium is essentially non-reactive. The potential and kinetic energies of the sound transmitted would therefore be equal. That component which is transmitted to the medium and completely reflected at the walls produces an ideal standing wave system. In such a system along the direction of the standing wave the total energy is alternately all kinetic and all potential and since this transition takes place the potential and kinetic energies must be equal.

Considering the room volume V, the average energy density would be

$$\bar{E} = \frac{1}{\rho c^2 V}\int\int\int p^2 dv. \tag{7}$$

If the loud speaker emits power into the room at a rate P_A, the average energy density in the room after a steady state has been reached is

$$\bar{E} = \frac{4P_A}{ac},^4 \tag{8}$$

[3] "The Dynamical Theory of Sound," Lamb, p. 208, Second Edition.
[4] "Theory of Vibrating Systems and Sound," Crandall, p. 210.

where a is the absorbing power of the room obtained from the sum of the products of the areas of the absorbing surfaces in the room and their respective absorption coefficients. From (7) and (8) the acoustic power delivered by the loud speaker could then be expressed in terms of the excess r.m.s. pressure throughout a large room as follows:

$$P_A = \frac{a}{4V\rho c}\int\int\int p^2 dv \tag{9}$$

and the efficiency of the loud speaker would therefore be

$$\begin{aligned} \eta = \frac{P_A}{P_E} &= \frac{\dfrac{a}{4V\rho c}\displaystyle\int\int\int p^2 dv}{\dfrac{e^2}{4r}} \\ &= \frac{K'\displaystyle\int\int\int p^2 dv}{\dfrac{e^2}{r}}. \end{aligned} \tag{10}$$

Response.—By determining the mean square pressure at all points in the measuring room or at all points on the surface of a large sphere in an infinite medium as discussed above, it is therefore possible to measure the "efficiency" of a loud speaker with a pressure indicating device. Such a method for determining the merits of a loud speaker at all frequencies of usual interest, however, would obviously be quite impracticable. Furthermore, unless the radiation from the loud speaker is uniform over a spherical surface it is not of particular interest to know the magnitude of the total acoustic power or the value of the quantity η since the configuration of the sound field about a loud speaker may change decidedly with frequency, with the result that variations in sound loudness at different frequencies in a particular region may be large even though the total power output from the loud speaker may be constant. In order then that the measured characteristic shall convey a true idea of the performance as it might be observed by the ear, the square of the pressure at one representative listening position or the average of the squares of the pressures in a small region wherein an observer might normally be located may be considered instead of the average throughout the room. In this manner a sort of specific efficiency measure would be obtained in that it is a measure of the efficiency with respect to the acoustic power transmitted through the specified position or region. Throughout the remainder of this paper, this specific measure of the efficiency is called

the "response" of the loud speaker as measured at a specified position or positions and is expressed in transmission units (TU) relative to a fixed arbitrary reference condition of 1 volt, 1 ohm, and 1 bar. In other words the acoustic power density at a specified position or the average acoustic power density at specified positions in the medium produced by the loud speaker under test per unit of available electrical supply power, is expressed relative to the acoustic power density produced by a fictitious standard loud speaker which when placed in the location of the loud speaker under test will produce a mean square pressure of one unit at the specified position or positions in the room when the ratio

$$\frac{e^2}{r} = 1.$$

The response in TU is thus expressed by the relation:

$$\mathrm{TU} = 10 \log_{10} \frac{\dfrac{K'\overline{p^2}}{\dfrac{e^2}{r}}}{K'\dfrac{\dfrac{1}{1^2}}{1}} = 10 \log_{10} \frac{\overline{p^2}}{\dfrac{e^2}{r}}$$

$$= 20 \log_{10} \frac{\bar{p}}{\dfrac{e}{\sqrt{r}}},$$

where $\bar{p}$ is the r.m.s. pressure at a specified position or the square root of the mean square r.m.s. pressures at specified positions in the medium; and e and r are as defined above.

Measuring Considerations in a Reflectionless Medium.—In a medium where there are no sound reflections from the bounding surfaces, two factors are most likely to cause the measured response of a loud speaker to vary with frequency. These factors are independent and their effects of about equal importance. The first and most apparent is the inherent dynamical characteristics of the loud speaker which involves its ability to transfer maximum power from the electrical supply to the acoustic medium. Any variation with frequency in the acoustic power output of a loud speaker when supplied by constant, available electrical power will, of course, cause corresponding variations in the response provided the square of the pressure at the measuring position is indicative of the power transmitted through this position. In order that this latter condition be strictly true, the measuring position in general should be, at a distance from the loud speaker,

large compared to the dimensions of the radiating surface. Otherwise, the wave front at the measuring position would not be spherical and the indicated pressure might result largely from the cyclic storage and absorption of energy by the loud speaker in the immediate vicinity of the radiator. With a proper location of the condenser transmitter, however, a response-frequency characteristic provides a useful measure of the dynamical perfection of a loud speaker.

The second factor which may cause large variations in the response of a loud speaker in a reflectionless medium is the change in the space distribution of the radiated sound with frequency. Although the total acoustic power delivered by a loud speaker may be constant, the power density at certain positions in the medium may change greatly with frequency due to the interference of sound originating at different parts of the radiating surface. Unless the radiation from the loud speaker is spherical, this interference phenomenon will result in a concentration of sound power in certain regions in the medium and a diminution in others. The locations of these regions change with frequency, radiator dimensions and the mode of vibration of the radiating surface.

For the case of a piston diaphragm radiator in a large rigid wall, it is possible to calculate the variations with frequency in the excess pressure at points in the sound field. Such calculations [5] and confirming experimental data show that in the sound field along the center perpendicular (a line normal to the surface of the piston at the center) to a piston radiator there is a succession of sound pressure maxima and minima out to a distance equal to approximately $\frac{D^2 f_1}{4500}$ feet (where D is the piston diameter and f_1 is the energizing frequency). Beyond this distance these maxima and minima points disappear and the pressure varies inversely as the distance. If then, the response of a loud speaker with a piston diaphragm is measured with the condenser transmitter at a distance less than $\frac{D^2 f}{4500}$ feet (where f is the highest measuring frequency), the response-frequency characteristic will have a succession of peaks and depressions which are independent of but which may be difficult to distinguish from those caused by poor dynamical characteristics of the loud speaker itself. On the other hand, if the condenser transmitter is located at any distance greater than $\frac{D^2 f}{4500}$ feet, the response-frequency characteristic obtained will not

[5] "The Directional Effect of Piston Diaphragms," Backhaus and Trendelenburg, *Zeitschrift f. Techn. Physik.*, Vol. 7, pp. 630–635, 1926. Also "Theory of Vibrating Systems and Sound," Crandall, pp. 137–149.

have abrupt irregularities due to interference and any two curves so obtained will only differ in magnitude. A curve obtained under this latter condition would therefore show the response-frequency variations as these would be observed at any distance greater than $\frac{D^2f}{4500}$ feet in this same direction.

While the above facts relate to a piston diaphragm radiator because more definite statements can be made regarding its sound field, similar effects due to the irregular distribution of the sound field are involved in the case of any other loud speaker which does not radiate as a pulsating sphere. Using such piston diaphragm considerations as a basis it has been found possible to predict suitable measuring conditions for any particular loud speaker. The fundamental requisite is that the pressure indicator be located at a distance from the loud speaker commensurate with the typical listening distance in order that the response-frequency characteristic shows variations which would normally be observed and which are therefore of interest. If, however, the typical listening distance is greater than $\frac{D^2f}{4500}$ feet (where D is roughly the diameter of the radiating surface and f is the highest measuring frequency) response-frequency measurements at this distance will show the response-frequency variations at any greater distance in the same direction so that measurements at the greater distances would not be necessary. If the most likely position of a listener is at a distance less than $\frac{D^2f}{4500}$ feet, the response-frequency characteristic obtained with the condenser transmitter at such a position will have irregularities due to interference but since these irregularities would be heard they should be charged against the loud speaker and such a curve would be indicative of the performance. In this latter case response measurements at a distance greater than $\frac{D^2f}{4500}$ feet are sometimes valuable for loud speaker design work in order to distinguish those variations due to poor dynamical characteristics of the loud speaker itself and those due to poor sound field distribution characteristics.

Measuring Considerations in a Medium with Reflections.—If the sound energy reflected to the condenser transmitter position from the bounding surfaces of the medium is comparable in magnitude with the energy reaching this position directly from the loud speaker, standing waves will exist and the sound pressure may vary greatly with frequency at any fixed transmitter position although the acoustic power

transmitted through this position may be constant. Response measurements with the condenser transmitter at any one position can therefore mean very little under such conditions.

To our knowledge it is practically possible only by working outdoors under very particular conditions to obtain a medium sufficiently free from reflections to make suitable response measurements at all frequencies with the condenser transmitter located at any one position. By using a room with all dimensions very large compared to the distance between the condenser transmitter and the loud speaker (which distance is determined by the size of the loud speaker and the highest measuring frequency as discussed above) and covering the walls with sound absorbing material, it is possible to reduce the reflected energy at the transmitter position to a small value over a considerable frequency range but any practical method of reducing the reflected sound to a negligible value at all frequencies of interest in loud speaker measurements is as yet not available.

In a plane standing wave system the energy density at points of maximum pressure or minimum velocity is equal to $\frac{p^2}{\rho c^2}$, where p is the r.m.s. pressure at these points. The locations of these maximum pressure points change with frequency but if the position of the condenser transmitter in loud speaker response measurements is changed at each measuring frequency to a maximum pressure point within a suitable region the indicated pressure will be a measure of the energy transmitted through this region. The measured response would then be approximately the same as would be measured in a reflectionless medium except for a magnitude difference due to the addition of the reflected energy. Such a procedure for loud speaker response measurements indoors would thus be suitable if it were not for the fact that the standing wave system in the room is usually of a very complicated configuration in three dimensions instead of being simple. The probability of being able to locate a position in any desired region of the sound field of a loud speaker where the pressures of each of the standing waves which may traverse this position are a maximum, is obviously remote.

A method of response measurement making use of the mean square pressure instead of the maximum value is more practicable. With a single frequency sinusoidal sound source, the pressure-space distribution of each of the standing waves in a room is likewise sinusoidal. The maximum r.m.s. pressure squared of each standing wave would then be twice the mean r.m.s. pressure squared over a half wave-length or any multiple of a half wave-length; also approximately twice the mean over

any distance large compared to a wave-length since this latter average approaches the half wave-length mean. The mean square pressure is therefore just as suitable as the maximum value as a measure of the energy density and further, it lends itself more readily to the determination of the energy density in the case where there are standing waves in several directions. For this latter case the energy density within a specified region is proportional to the mean square pressure in all directions or at all points within the volume of a sphere having a diameter large compared to the wave-length. The response of the loud speaker at any frequency can accordingly be measured in a room with reflections by averaging the squares of the pressures throughout a suitable volume.

The above method of response measuring indoors however, is not entirely independent of the measuring room. If the reflected energy is large the response measurements will be affected by the variation in the absorption power of the room with frequency so that a large room with absorbing material having as uniform and large absorption characteristics as possible over the measuring frequency range is still desirable. Some sound absorbing materials have uniform absorption characteristics but when this is the case the absorbing power is apt to be very low. The use of such materials results in extremely large pressure variations within the room so that a measuring device having a sufficient amplitude range to average the squares of the pressures is difficult to obtain. For this reason and because of the fact that the region through which it is necessary to average the squares of the pressures at low frequencies becomes prohibitive, a large room is most desirable so that the difference between the direct and reflected energies at the transmitter position will be as large as possible. Indoor measurements under these conditions approach infinite medium measurements.

The use of a large room also results in less reaction of the room inclosure on the loud speaker itself. While under most conditions such reactions have little effect on the acoustic output power of the loud speaker, in small measuring rooms at very low frequencies where the absorption is low and the radiator of the loud speaker (perhaps designed for a large auditorium) is large, the phase and magnitude of the reflected energy at the radiating surface of the loud speaker may be such as to cause large variations in the acoustic impedance of the medium on the area adjacent to this surface. This variation in the acoustic impedance of the loud speaker load will cause variations in the acoustic power density at the transmitter position. Response measurements on loud speakers of large dimensions and particularly measure-

ments on such devices at very low frequencies are consequently more indicative of the capabilities of the loud speaker when obtained outdoors or in a very large room.

Experimental Data

General.—To determine the extent to which the above discussed acoustic effects may influence the result of a loud speaker performance measurement and to show the measuring conditions under which such acoustic factors are encountered, response-frequency characteristics of loud speakers were measured under various acoustic conditions. These are described in the following paragraphs.

In all these measurements a calibrated condenser transmitter approximately $2\frac{7}{8}''$ in diameter was used as the acoustic detector. The thermophone calibration on this transmitter showed that with constant pressure on the diaphragm the voltage produced between the grid and filament of the associated vacuum tube was very nearly independent of frequency. Corrections for such small variations as did exist however have been made in all the following curves. In addition a tapered correction of .6 TU per 100 cycles increased in frequency between 1,100 and 2,100 cycles and a constant correction of 6 TU for frequencies above 2,100 cycles have been subtracted from the response measurements to correct for the fact that the indicated pressure approaches twice the free space pressure at frequencies at which there is reflection from the diaphragm. This latter correction was obtained by making response-frequency measurements on a loud speaker under a fixed set of conditions; first, with the condenser transmitter freely suspended in the sound field as in all the following curves and then with the transmitter located at the center of a round baffle 12″ in diameter. When in the baffle complete sound reflection from the transmitter occurred at a frequency lower than that at which reflection began to take place from the transmitter alone. From the difference between the two response-frequency curves so obtained, it was therefore possible to definitely locate the transition frequency range between 1,100 and 2,100 cycles and to evaluate the transmitter reflection correction.

The number of measurements made in order to define any response-frequency characteristic depended upon the nature of the curve. If no abrupt changes in the response were observed in making the measurements, approximately 10 measurements per octave were obtained. Otherwise the frequency of the oscillator was changed by small steps and a sufficient number of measurements made to clearly define the curve.

Measuring System.—The circuit arrangement of the measuring system used in making the measurements is shown in schematic form on Fig. 1. An oscillator having a suitable frequency range and power output was alternately connected by means of a two-position switch through a transformer to the loud speaker under test and to the input terminals of an attenuator calibrated in TU. The transformer had a ratio such that the loud speaker being measured was always connected to an impedance equal to that for which it was designed to be connected. The condenser transmitter in series with the output terminals of the attenuator and located in the medium as will be discussed later, was connected to a voltage indicating system consisting of an amplifier, a thermocouple and a meter. A low-pass filter was included in the

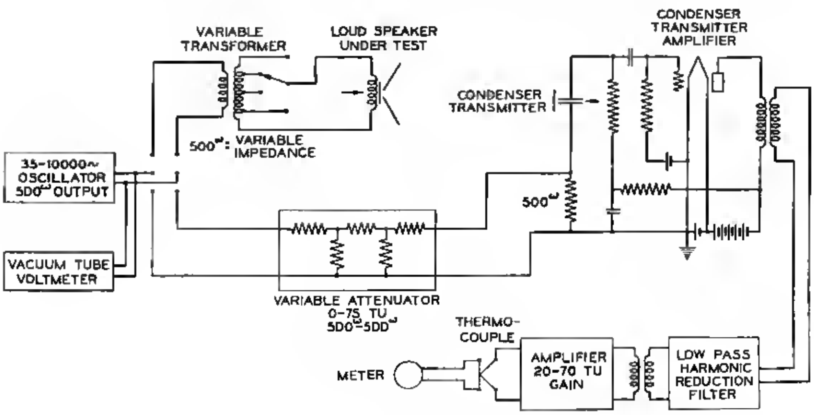

Fig. 1—Schematic circuit of loud speaker response measuring system.

indicating system as shown to insure that only the fundamental frequency of the output from the condenser transmitter or attenuator was indicated. The measuring procedure was as follows: The output or terminal voltage of the oscillator when open-circuited or connected to the attenuator was kept constant at all frequencies by means of a vacuum tube voltmeter. With the loud speakers considered the sound output over a wide magnitude range was proportional to the oscillator voltage so that the magnitude of this voltage was governed entirely by the sound pressure in the medium most suitable for making measurements. With the oscillator connected to the loud speaker (through the transformer) the sensitivity of the voltage indicating system was adjusted at each frequency until a mid-scale deflection of the meter was obtained as a result of the voltage generated by the condenser transmitter. After each adjustment the oscillator was then switched from

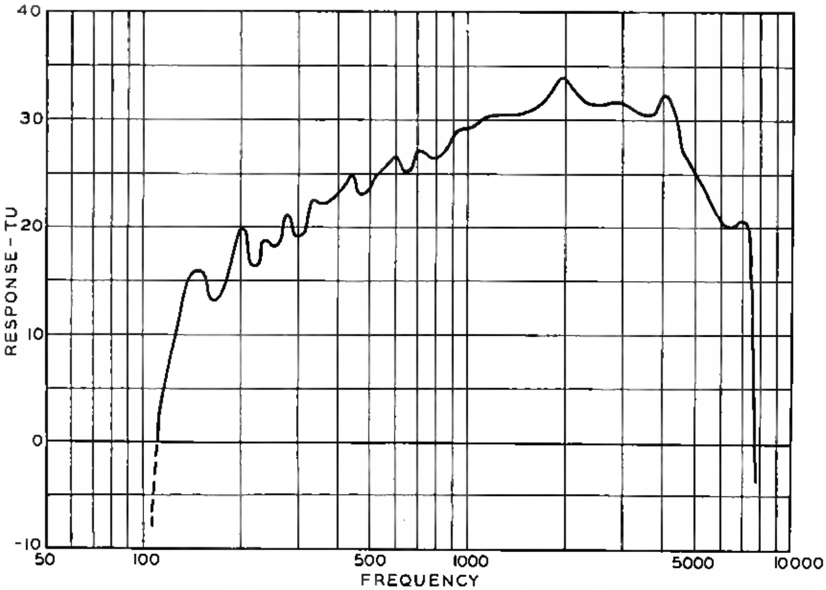

Fig. 2—Response-frequency characteristic of 115 cycle cut-off exponential horn with moving coil type receiver. Measured outdoors at a distance of 12′ from horn mouth on the axis.

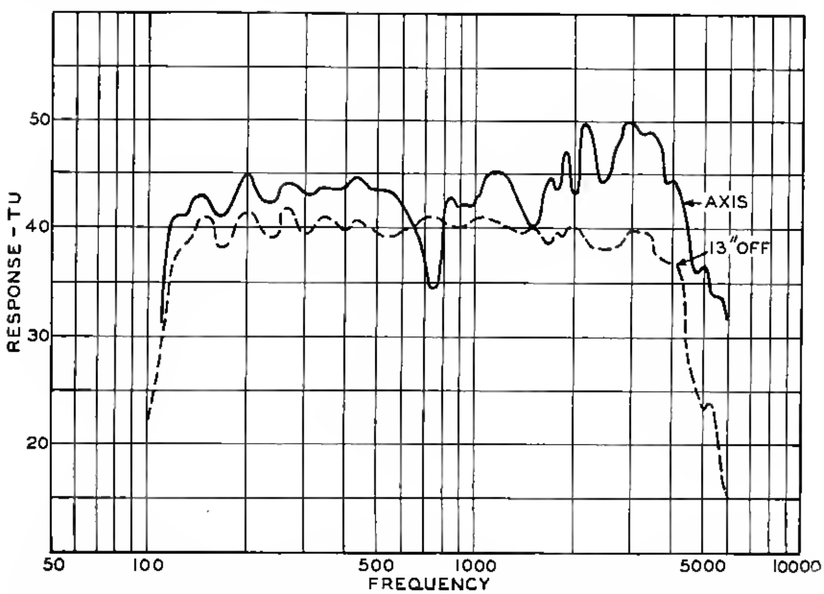

Fig. 3—Response-frequency characteristics of 115 cycle cut-off exponential horn with moving coil type receiver. Measured outdoors 2″ from plane of horn mouth with center of condenser transmitter diaphragm on horn axis and 13″ from axis.

the loud speaker to the input terminals of the attenuator and the attenuator adjusted to give the same meter deflection. The variations in the attenuator settings with frequency showed the variations in the performance of the loud speaker in TU. When the ratio of the open-circuit voltage of the oscillator to the square root of its output impedance equalled 1, the setting of the attenuator which gave a voltage between the attenuator output terminals equal to the voltage across the condenser transmitter terminals with a pressure of one bar on the diaphragm, gave the reference zero of one volt, one ohm, and one bar

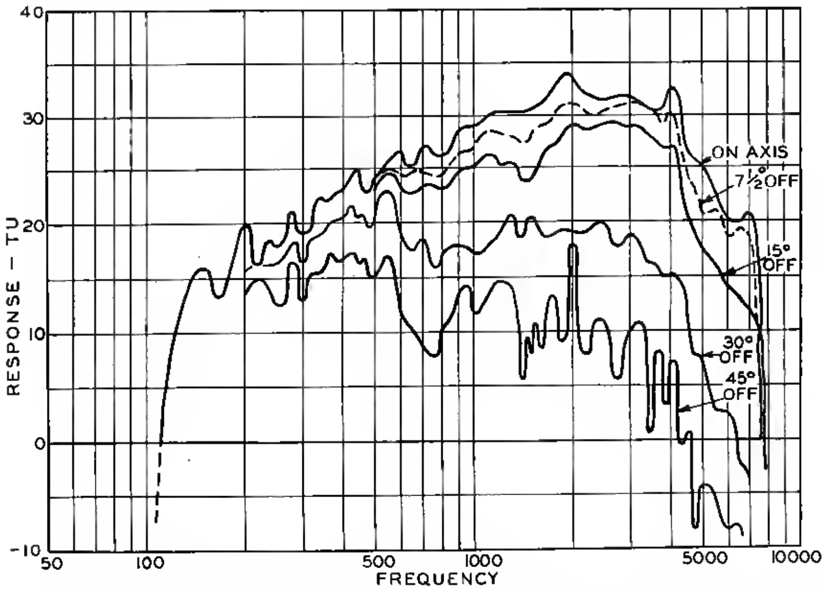

Fig. 4—Response-frequency characteristics of 115 cycle cut-off exponential horn with moving coil type receiver. Measured outdoors 12 feet from horn mouth at the specified angles with the axis.

described above. The response of the loud speaker was then read directly from the attenuator setting.

This measuring method has the commendable feature that the results obtained are independent of any variations from day to day in the sensitivity in the voltage indicating system. The voltage indicating system simply serves to compare the voltage produced by the condenser transmitter with the voltage across the output terminals of the attenuator and any variations in battery voltage, tubes, etc., or any variations in the amplification with frequency can in no way affect the accuracy of the measurements. Aside from the condenser transmitter, the only element in the measuring system which must be calibrated and

maintain its calibration closely, is the attenuator which involves only a group of resistances.

Outdoor Measurements.—As an illustration of those acoustic effects involved in loud speaker measurements in a reflectionless medium, the following response data obtained outdoors in an open field will be of

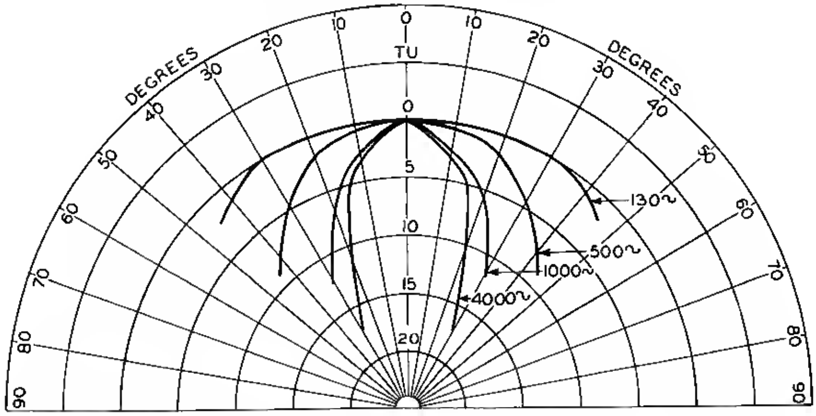

Fig. 5—Polar curves showing response (expressed relative to the axis response) of 115 cycle cut-off exponential horn with moving coil type receiver at various angles from horn axis and 12 feet from the mouth.

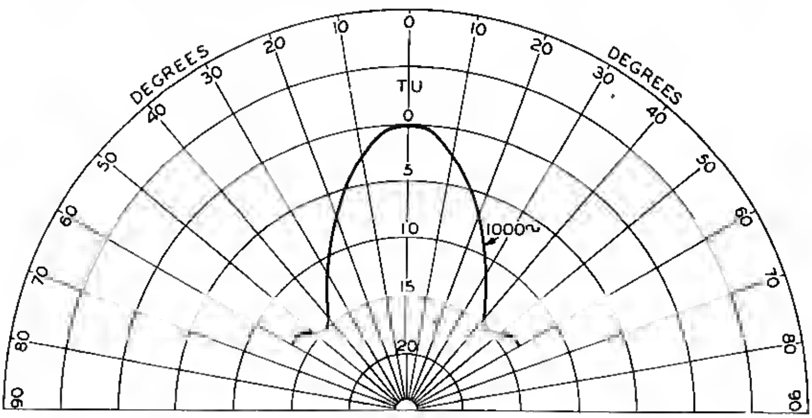

Fig. 6—Polar curve showing response (expressed relative to the axis response) of 115 cycle cut-off exponential horn with moving coil type receiver at different angles from axis and at a distance of 12 feet from center of horn mouth.

interest. Two loud speakers having uniform sound power output over a wide frequency range so that the dynamic characteristics would not obscure the acoustic effects were used. The loud speakers were placed at the edge of a skeleton platform approximately 15′ above the ground and the condenser transmitter suspended at various positions

in the sound field. Care was taken to suspend the transmitter and its small associated amplifier between small poles in such a way that any possible reflections from such objects in the sound field would not reach the transmitter position. As for reflections from the ground, the distance of the loud speaker from the ground with the consequent sound divergence from the radiating surface, and also the absorption and diffraction at the ground, caused by the magnitude of the sound reflected to the transmitter position to be quite undetectable.

One of the loud speakers was a 115 cycle cut-off exponential horn with a moving coil type receiver.[6] The mouth of the horn was located at the platform edge with the axis making an angle upward from

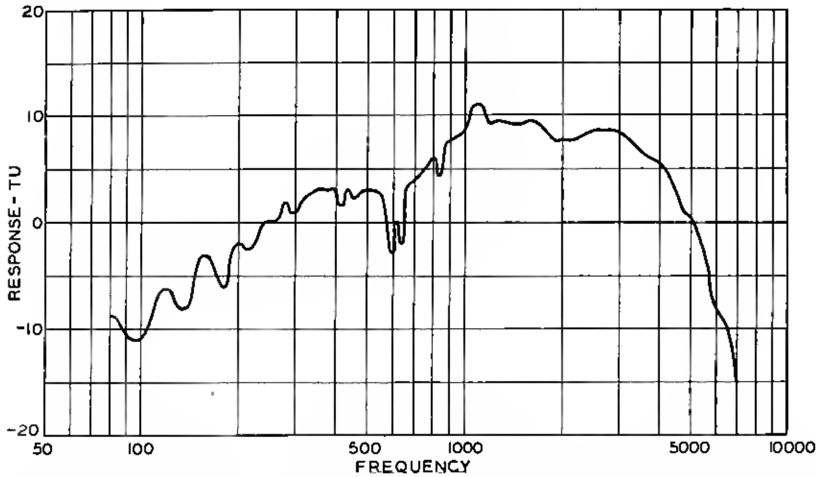

Fig. 7—Response-frequency characteristic of $3\frac{1}{2}''$ piston diaphragm loud speaker. Measured outdoors 12 feet from and on a line perpendicular to the center of the diaphragm.

the horizontal of approximately 15°. Fig. 2 shows the response frequency characteristic with the condenser transmitter on the axis at a distance of 12′ from the mouth. Except for variations near the horn cut-off frequency due to the horn itself, note the absence of any large irregularities and also the rising trend of the curve with frequency. The diameter of the horn mouth was 30″ so that 12′ is greater than the distance $\frac{D^2f}{4500}$ feet discussed above.

Fig. 3 shows response-frequency characteristics of the same loud speaker measured under exactly the same conditions except that the condenser transmitter was located on the axis only 2″ from the horn

[6] This type of receiver was described by Wente and Thuras in *The Bell System Technical Journal*, for January, 1928.

mouth. This curve differs considerably from the one obtained at a distance of 12′. The marked depression in the curve at 750 cycles checks very closely the first interference frequency as calculated for a piston radiator approximately 30″ in diameter and allowing for a slight contraction of the radiating surface as the frequency is increased (which assumption would be quite reasonable for the horn), the irregularities at the higher frequencies are also explained in the same manner. For the piston, however, the minimum pressure point would be zero, which fact indicates that the wave-front at the horn mouth either is not plane or is not of uniform intensity over the radiating surface. Below 1,000 cycles the average trend of this curve is very nearly parallel to the axis of abscissæ while as noted for the curve

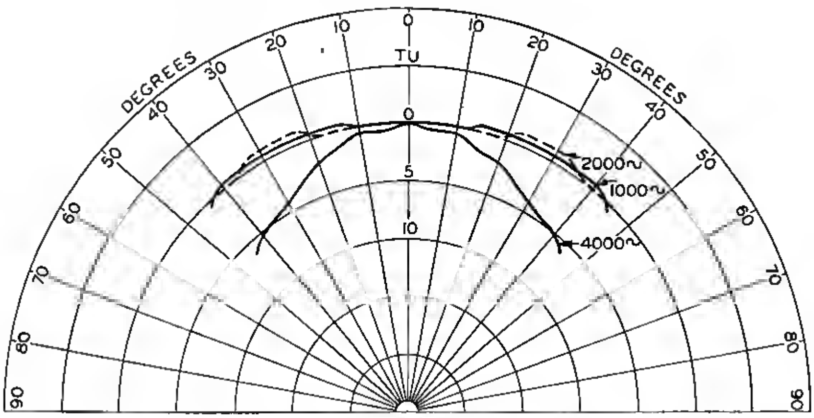

Fig. 8—Polar curves showing response (expressed relative to axis response) of 3½″ piston diaphragm loud speaker at various angles from perpendicular to center of diaphragm and 12 feet away.

obtained at a distance of 12′, there is a very definite downward slope. This is as would be expected if there were an increasing concentration of the sound field about the axis as the frequency increased. The fact that there is such a varying concentration is shown by the data on Fig. 4. These curves were obtained with the condenser transmitter at a distance of 12′ in each case, but with a line from the center of the horn mouth to the center of the transmitter making various angles with the horn axis as specified. In making these measurements, the transmitter remained fixed and the horn was rotated upward in a vertical plane about the center of the mouth. It is apparent from these curves that as the angle is increased the response at the higher frequencies becomes lower, while at lower frequencies the change is slight. The irregularities in the 45° curve are probably due to inter-

ference. Note that a curve of almost any desired trend may be obtained by locating the condenser transmitter at the proper position.

On Fig. 5 the data of Fig. 4 are plotted on polar coordinate paper to show more clearly the approximate manner in which the sound field varies. On these curves the magnitude of the response is expressed relative to that on the axis and the approximate distribution at each of four frequencies is shown. At the larger angles if a sufficiently large number of measurements are made an irregular interference pattern is obtained like that shown on Fig. 6 for 1,000 cycles.

The second loud speaker measured consisted of a $3\frac{1}{2}''$ piston diaphragm (inertia control) mounted in one side of a cubical box approxi-

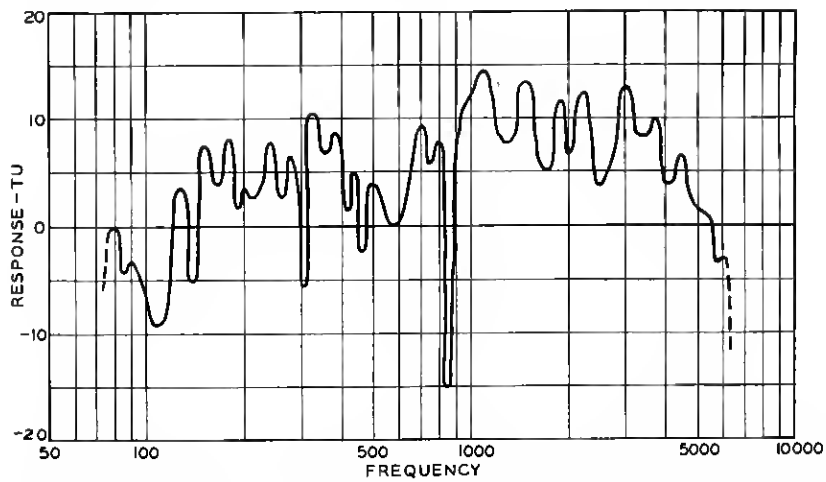

Fig. 9—Response-frequency characteristic of $3\frac{1}{2}''$ piston diaphragm loud speaker. Measured in highly absorbing room 12 feet from and on a line perpendicular to the center of the diaphragm.

mately 12″ on a side and filled with wool. This loud speaker was thus of a radically different type from the first and was chosen because the size and nature of the diaphragm was such that any reaction of the medium on its vibration amplitude would be unlikely. A direct comparison of its performance under one medium condition with that under another would therefore be justifiable. The response-frequency characteristic of this loud speaker as measured outdoors with the condenser transmitter at a distance of 12′ on the diaphragm center perpendicular is shown on Fig. 7. The irregularity in this curve at 600 cycles has been shown by other tests to be due to poor dynamical characteristics of the loud speaker itself.

On Fig. 8 are polar coordinate curves for the piston diaphragm loud

speaker similar to those shown on Fig. 5 for the horn type loud speaker. Note for the same frequency the greater concentration of the sound field in the case of the horn. This is due to its larger radiating surface. From these data it might be inferred that if the sound field of a loud speaker of either of these types is to be the same at all frequencies, the size of its radiating surface must decrease as the frequency increases.

Indoor Measurements.—Making use of the above described outdoor measurements as standards of comparison, response measurements were made indoors on the same loud speakers and at the same relative positions in the sound field in order to determine the magnitude of the effect of reflections on such measurements. The room available for

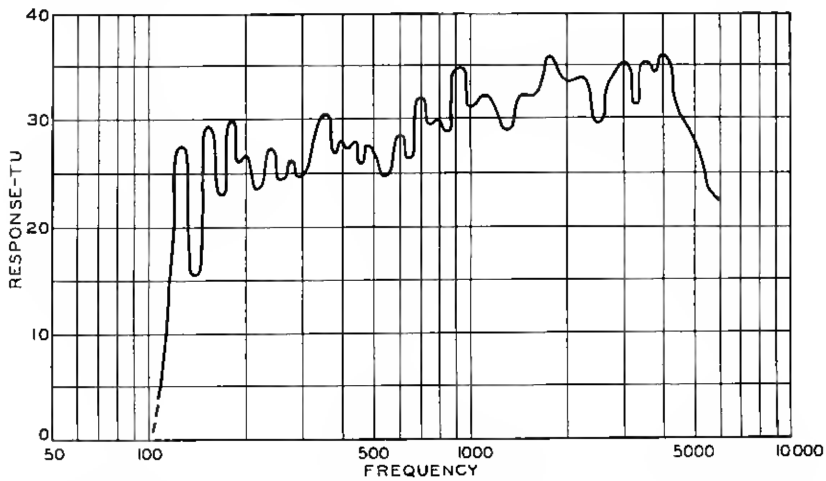

Fig. 10—Response-frequency characteristic of 115 cycle cut-off exponential horn with moving coil type receiver. Measured in highly absorbing room 12 feet from horn mouth on axis.

this work was approximately 34′ × 18′ × 9′. The six bounding surfaces of the room were covered with ½″ asbestos hair felt with heavy monks cloth curtains loosely and irregularly draped over the walls. The condenser transmitter and the loud speaker being measured were located along the major axis equi-distant from and on opposite sides of the center of the room and suspended about mid-way between the ceiling and the floor. A moderately large room with the usual precautions to eliminate reflections was thus used.

Fig. 9 shows the response frequency characteristic of the 3½″ piston diaphragm loud speaker as obtained in this room with the condenser transmitter located on the diaphragm center perpendicular at a distance of 12′. A comparison of this curve with that of the same loud

speaker obtained outdoors with the condenser transmitter at the same relative position in the medium gives an idea of the magnitude of the effect of room reflections even under comparatively favorable indoor measuring conditions. The same frequencies were measured in both the indoor and outdoor curves and no attempt was made to locate all the irregularities in the indoor curve.

Fig. 10 shows an indoor curve of the 115 cycle cut-off exponential horn measured in the same room and under the same conditions at a distance of 12′. The variations in this latter curve as compared to the outdoor curve shown on Fig. 2 appear to be less than in the case of the piston type loud speaker, probably because the horn is more directive,

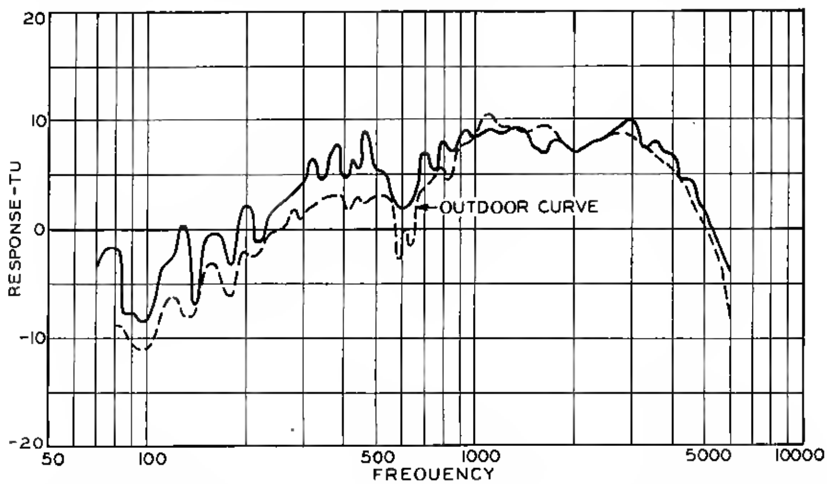

Fig. 11—Response-frequency characteristic of 3½″ piston diaphragm loud speaker. Measured in highly absorbing room 12 feet from diaphragm with rotating condenser transmitter.

resulting in a larger difference between the direct and the reflected sound energy at the transmitter position.

The variations in these two indoor response-frequency characteristics resulting from reflections could have been reduced by making the measurements in a much larger room treated with sound absorbing material in the same manner. Such a room for loud speaker measuring purposes is not usually available, but if sufficiently large and of a suitable shape does afford the most satisfactory indoor measuring conditions especially at very low frequencies.

Another method of obviating the effects of reflections is to measure the mean square pressure throughout a suitable volume as discussed previously. A practicable means of making such a mean square

pressure measurement and one which has been found to be quite satisfactory, consists in approximating the volume measurement by rotating the condenser transmitter in a circle 69″ in diameter, inclined 45° to the horizontal. A mechanism so arranged that the plane of the condenser transmitter diaphragm always remains perpendicular to the loud speaker axis is used and the condenser transmitter is connected to the same voltage indicating system described above. As noted, this indicating system involves a thermocouple and as a result, the meter deflection is very nearly proportional to the square of the input

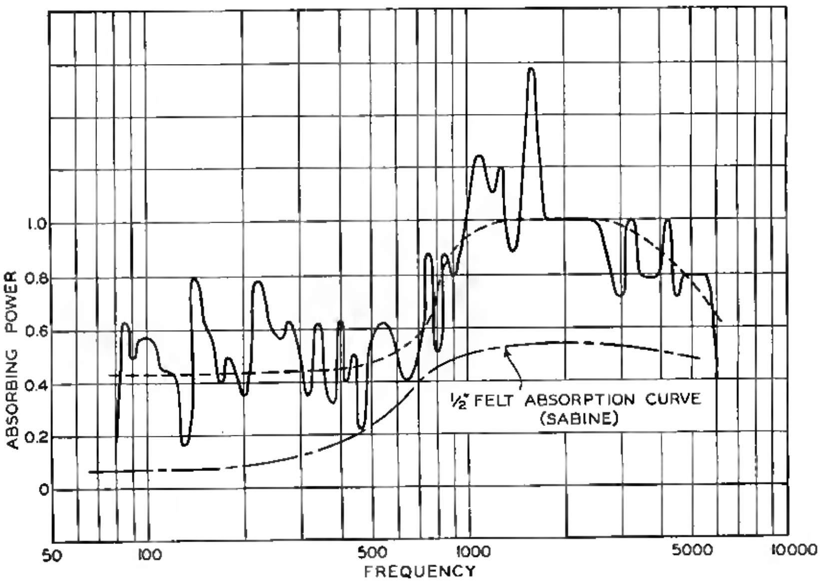

Fig. 12—Curve showing variation with frequency in the effective absorbing power of a felt lined room with respect to a region near the center and relatively near the sound source. Determined from loud speaker measurements in this room and outdoors as shown on Fig. 11.

voltage. As the condenser transmitter is rotated about the periphery of the circle, therefore, the average meter deflection is proportional to the average of the squares of the transmitter terminal voltages or the average of the squares of the pressures throughout the revolution.

Fig. 11 is a response-frequency characteristic of the piston diaphragm loud speaker measured in the same room and under the same conditions as the curve in Fig. 9 except with the rotating condenser transmitter. The center of the circle was located at the same point as the condenser transmitter for Fig. 9.

While rotating the transmitter in this manner does not average the

squares of the pressures throughout a volume, it does give a measure which is closely proportional to the power density. This is apparent from a comparison of Fig. 11 with a curve on the same loud speaker measured outdoors shown on Fig. 7 and replotted on Fig. 11 for comparison. Note that these two curves very closely coincide between 1,000 and 3,000 cycles. Below 1,000 cycles and above 3,000 cycles the uniformly greater response indoors can be explained in the following manner.

As given by equation (8) above, the average energy density in a room resulting from a loud speaker emitting sound power at a constant

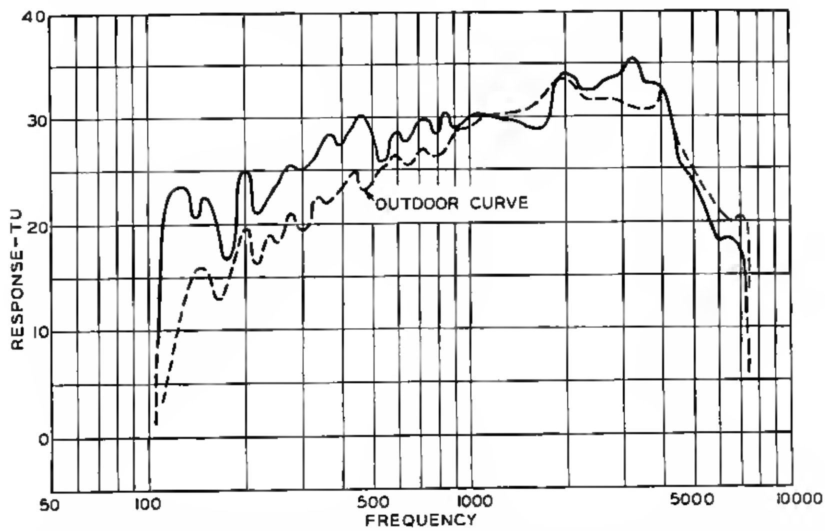

Fig. 13—Response-frequency characteristic of 115 cycle cut-off exponential horn with moving coil type receiver. Measured in highly absorbing room 12 feet from horn mouth with rotating condenser transmitter.

rate is inversely proportional to the absorbing power of the room. Inasmuch as the two curves in Fig. 11 were obtained with the same loud speaker with the condenser transmitter located at the same distance and at approximately the same relative position in the medium, the difference in the two curves would appear to be due only to the difference between the indoor and outdoor absorption. Assuming for the outdoor case a fictitious bounding surface making an enclosure of the same shape and size as the indoor room and that the energy striking this fictitious surface is completely absorbed (as would be the case) the area element of the factor "a" in equation (8) becomes the same for the indoor and outdoor tests, and the ratio of the indoor energy to the outdoor energy would therefore bear some simple

relation to the average absorption coefficient of the sound absorbing material of the indoor measuring room. From the ratios of the outdoor to indoor energy densities at different frequencies as determined from Fig. 11, the solid curve on Fig. 12 is obtained. The irregular character of this curve is probably due to the fact that the rotating indoor transmitter did not give an exact measurement of the energy density at each frequency. The trend of this curve, however, is quite definite as is indicated by the dotted curve which is an average curve obtained by inspection. A comparison of this mean curve with the dot-dash curve showing the approximate absorption power of a $\frac{1}{2}''$ layer of asbestos hair felt [7] indicates an interesting correlation in the trend of the two

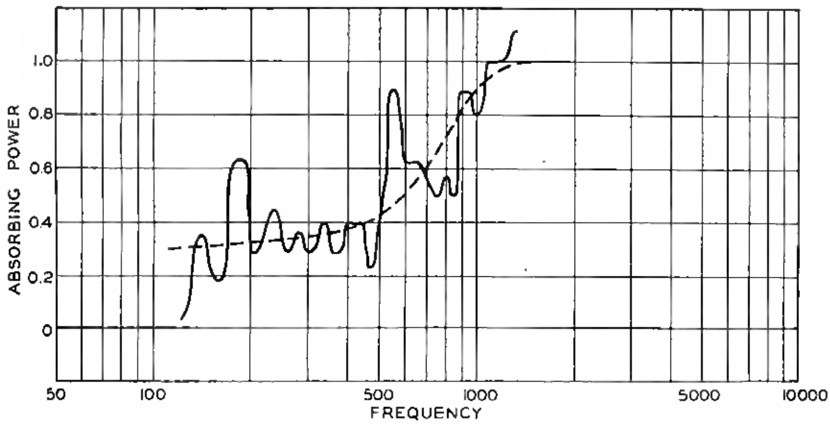

Fig. 14—Curve showing variation with frequency in the effective absorbing power of a felt lined room with respect to a region near the center and relatively near the sound source. Determined from loud speaker measurements in this room and outdoors, as shown on Fig. 13.

curves. The difference in magnitude is probably due to sound diffusion at the walls resulting in the ratio of the energy reflected to the energy direct from the source being smaller than would be the case were the measuring region located close to the absorbing surface.

The solid curve in Fig. 13 is a response-frequency characteristic of the 115 cycle cut-off exponential horn obtained with the rotating condenser transmitter under the same conditions as the curve in Fig. 11. The center of the horn mouth was placed at the same position as was the center of the diaphragm of the $3\frac{1}{2}''$ diameter piston radiator. The dotted curve in Fig. 13 is the outdoor characteristic obtained with the condenser transmitter on the horn axis at a distance of 12′. It will be noted that these indoor and outdoor curves diverge at the low

[7] See "Collected Papers on Acoustics," W. C. Sabine, p. 213, Fig. 4.

frequencies. From this divergence the absorption curve shown in Fig. 14 was obtained. Due to the relatively small angle subtended by the sound field of the horn at the higher frequencies, the indoor data where the condenser transmitter was rotated throughout a relatively large region in front of the horn, are not comparable with the outdoor data where the transmitter was located in one position on the horn axis.

Conclusion

From the above considerations it is obviously quite impossible to interpret the significance of response measurements on loud speakers in general unless such measurements are qualified by statements regarding the acoustic measuring conditions. Especially must information be given as to the position of the condenser transmitter relative to the loud speaker when the measurements were made, the method of measurement (pressure measured at one position or averaged within a region), and the size and nature of the medium. In general response measurements to be most indicative of the capabilities of the loud speaker should be made with the condenser transmitter at a distance from the loud speaker commensurate with or equivalent to the most likely listening distance of an observer.

To determine which of two loud speaker response-frequency characteristics is the better involves in addition to the above discussed acoustic considerations, an interpretation of the physiological significance of the magnitude and position in the frequency spectrum of departures in the curves from a straight horizontal line. Such an interpretation involves many physiological factors, the discussion of which is not within the scope of this paper. It should also be borne in mind that the response-frequency characteristics described in this paper are determined from steady state amplitude measurements and that they therefore give little information as to transient or phase distortion. However the cause of transient or phase distortion (the storage and release of energy in the reactive elements of the loud speaker) is also a cause of poor dynamical characteristics so that the peaks and depressions in a response-frequency characteristic may also be an indication of the phase and transient distortion. On the whole the response-frequency characteristic even though complicated by such a wide variety of factors has been found to be the most significant single criterion upon which to base a judgement of the merits of a loud speaker.